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None

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UK CL (Edition F) H4D

(54) A radar apparatus

(57) A radar includes an antenna (10) arranged to generate sum and difference signals V_s, V_D in respective channels C1, C2. Signals in the difference channel, corresponding to consecutive pulses, are shifted in phase by $\pm\pi/_2$ respectively, and their amplitudes modified adaptively by a weighting factor γ. The weighted and phase shifted signals are combined vectorially 18 with their respective sum signals to produce resultant signals which are compared in a two pulse canceller (20). Any residual signal is minimised in circuit (22) by suitably adjusting γ. The value of γ necessary to achieve a minimum at the output of the two pulse canceller is related to the component of angular velocity of a rotating target which is normal to the plane of the difference pattern of the antenna. A dual axis radar can be used enabling evaluation of two, orthogonal components of angular velocities of a rotating target (a ship undergoing yaw and roll movements). A single axis radar could also be used to eliminate Doppler broadening due to the effect of vertical wind shear on clutter.

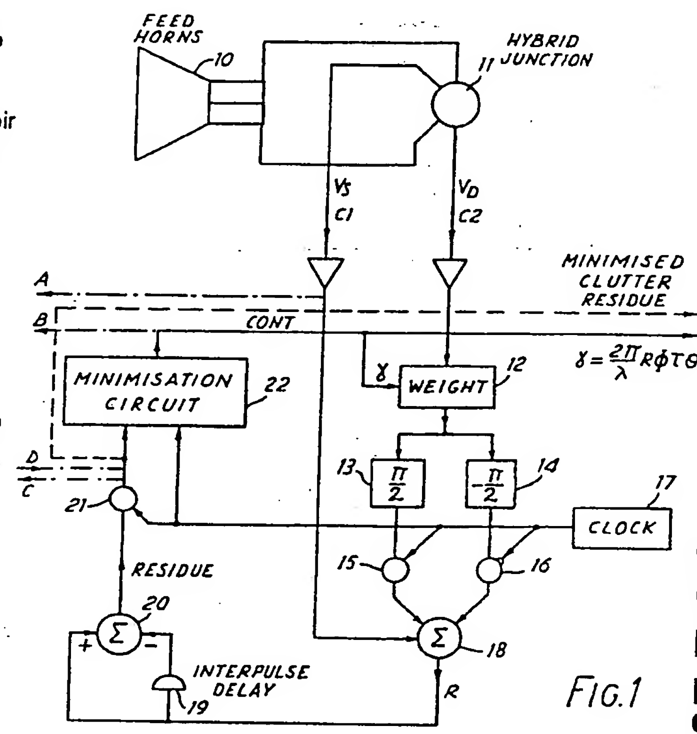


FIG.1

GB 2 260 234 A

At least one drawing originally filed was informal and the print reproduced here is taken from a later filed formal copy.

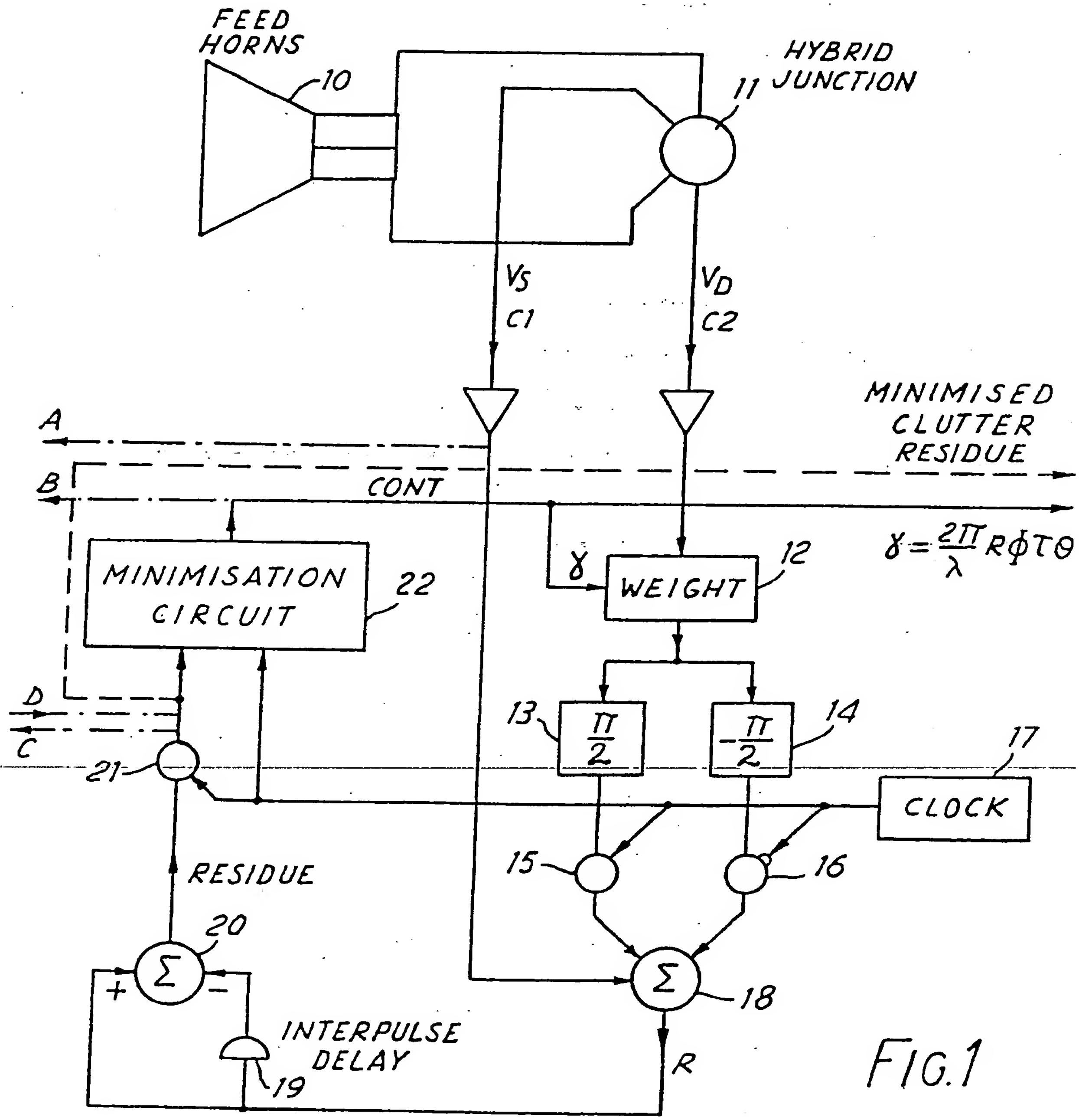
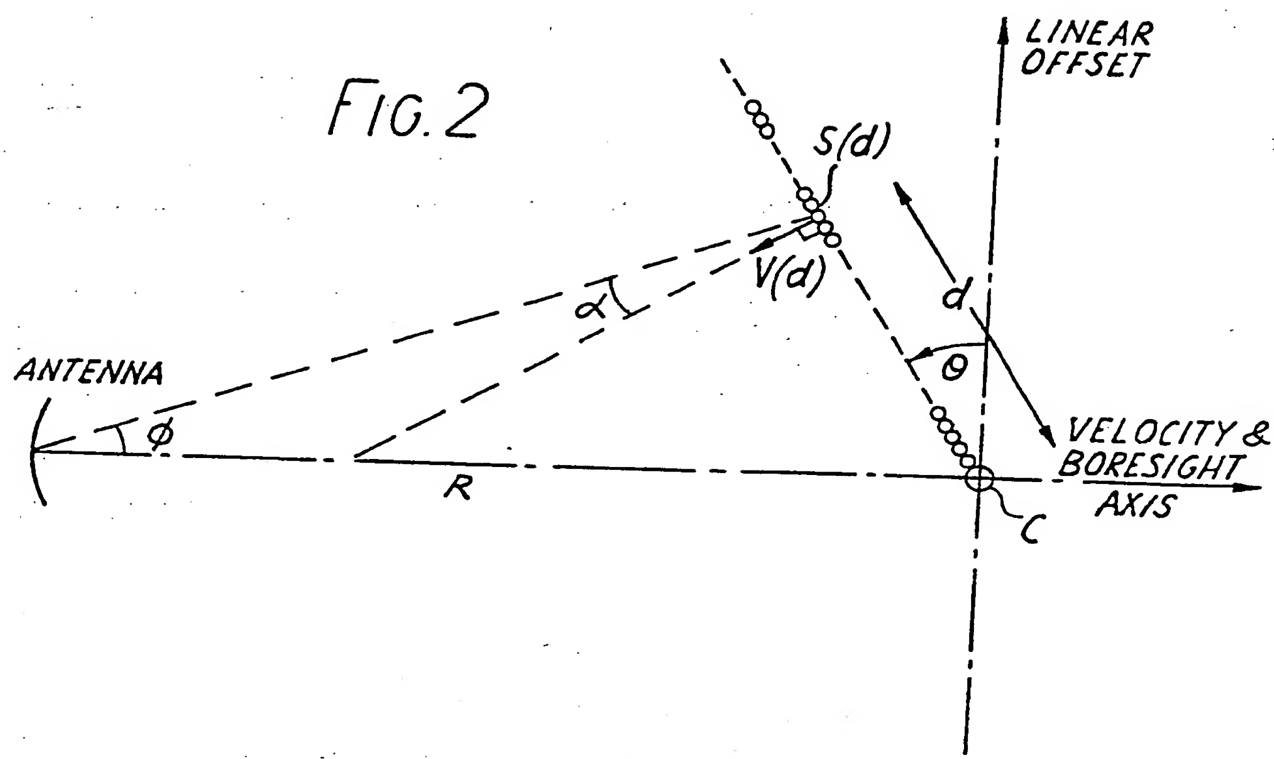

FEED HORNS
10
HYBRID JUNCTION
11
VS
C1
VD
C2
MINIMISED CLUTTER RESIDUE
A
B
CONT
$\gamma = \frac{2\pi}{\lambda} R\phi T\theta$
γ
WEIGHT
12
MINIMISATION CIRCUIT
22
D
C
21
13
π/2
-π/2
14
17
CLOCK
15
16
RESIDUE
20
Σ
+
−
18
INTERPULSE DELAY
19
R

FIG.1

FIG. 2


LINEAR
OFFSET
S(d)
V(d)
α
d
θ
ANTENNA
φ
R
VELOCITY &
BORESIGHT
AXIS
C

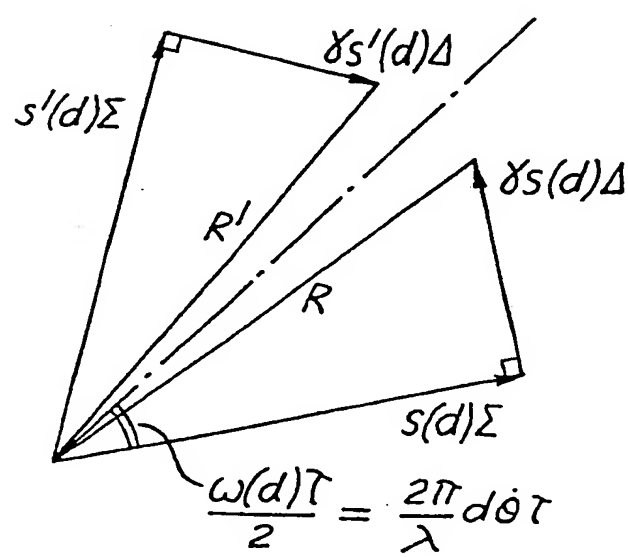

γs'(d)Δ
s'(d)Σ
R'
γs(d)Δ
R
s(d)Σ
$\frac{\omega(d)\tau}{2} = \frac{2\pi}{\lambda} d\dot{\theta}\tau$

FIG. 3

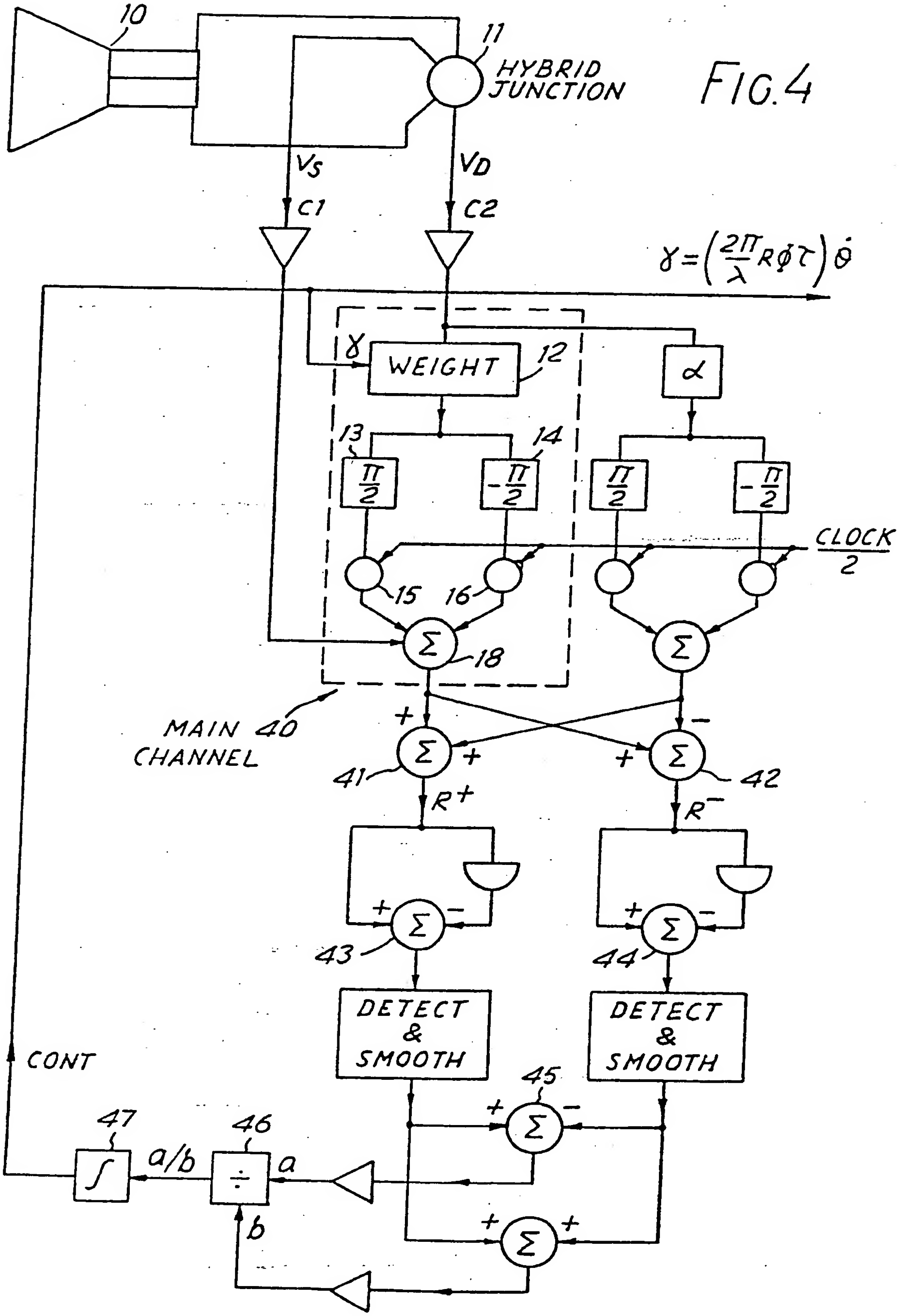
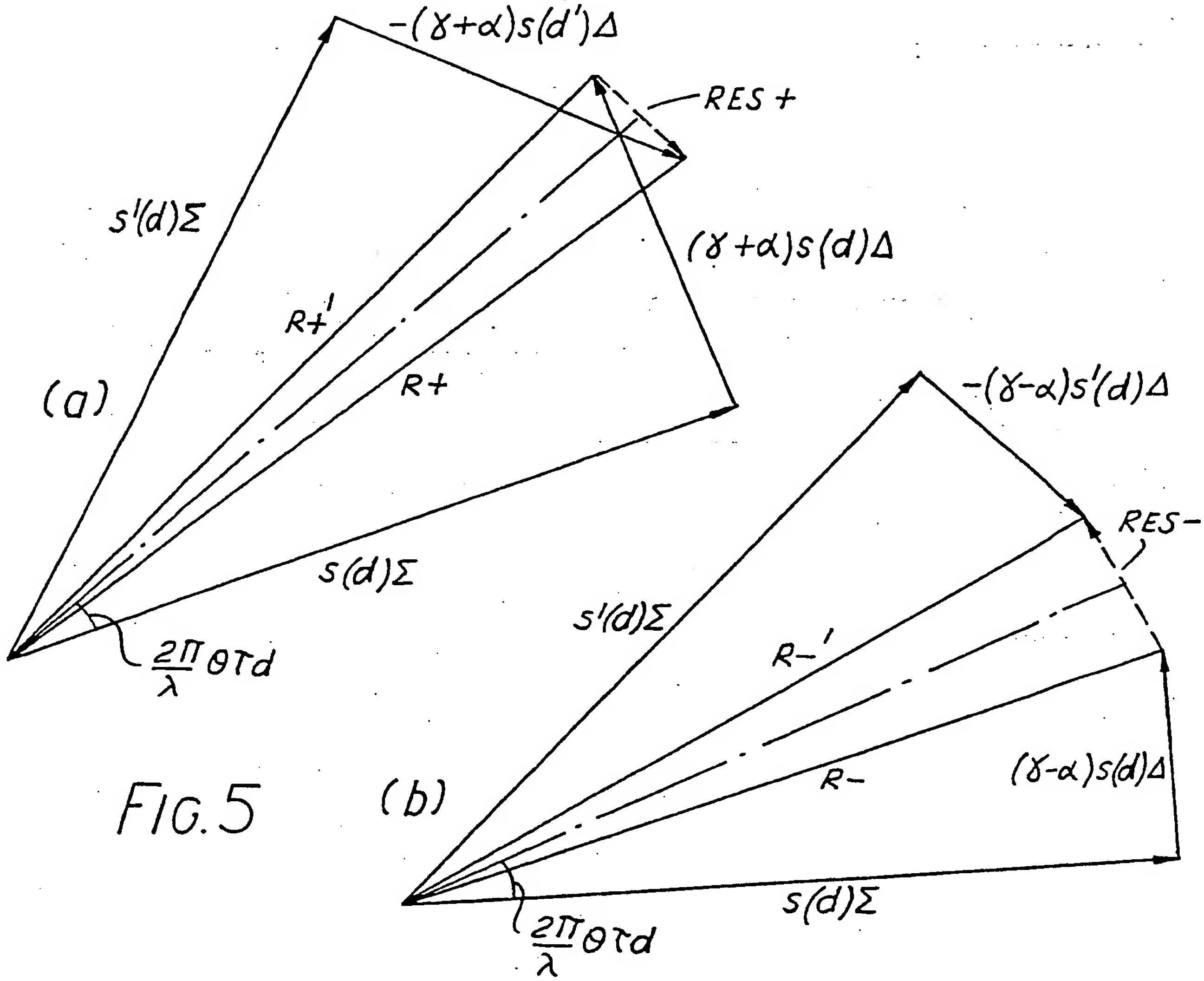
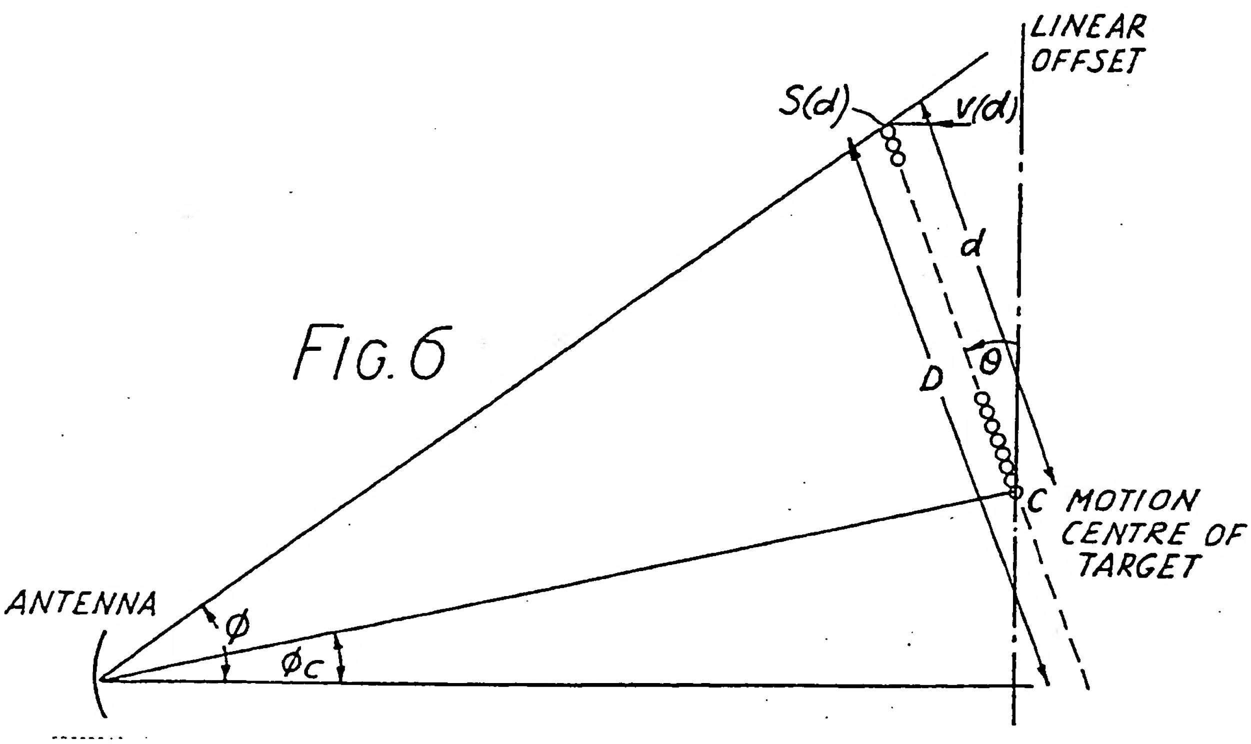

10
11
HYBRID JUNCTION
V_S
V_D
C1
C2
$\gamma = \left(\frac{2\pi}{\lambda} R \phi \tau\right) \dot{\theta}$
γ
WEIGHT
12
α
13
14
$\frac{\pi}{2}$
$-\frac{\pi}{2}$
$\frac{\pi}{2}$
$-\frac{\pi}{2}$
CLOCK
2
15
16
18
MAIN 40
CHANNEL
+
−
+
+
41
42
R^+
R^-
43
44
DETECT & SMOOTH
DETECT & SMOOTH
45
CONT
47
46
a/b
a
b

FIG.4



−(γ+α)s(d′)Δ
RES +
s′(d)Σ
(γ+α)s(d)Δ
R+′
R+
(a)
s(d)Σ
2π/λ θτd
−(γ−α)s′(d)Δ
RES−
s′(d)Σ
R−′
(γ−α)s(d)Δ
R−
(b)
s(d)Σ
2π/λ θτd

FIG. 5



LINEAR
OFFSET
S(d)
V(d)
d
θ
D
C
MOTION
CENTRE OF
TARGET
ANTENNA
φ
φc

FIG. 6

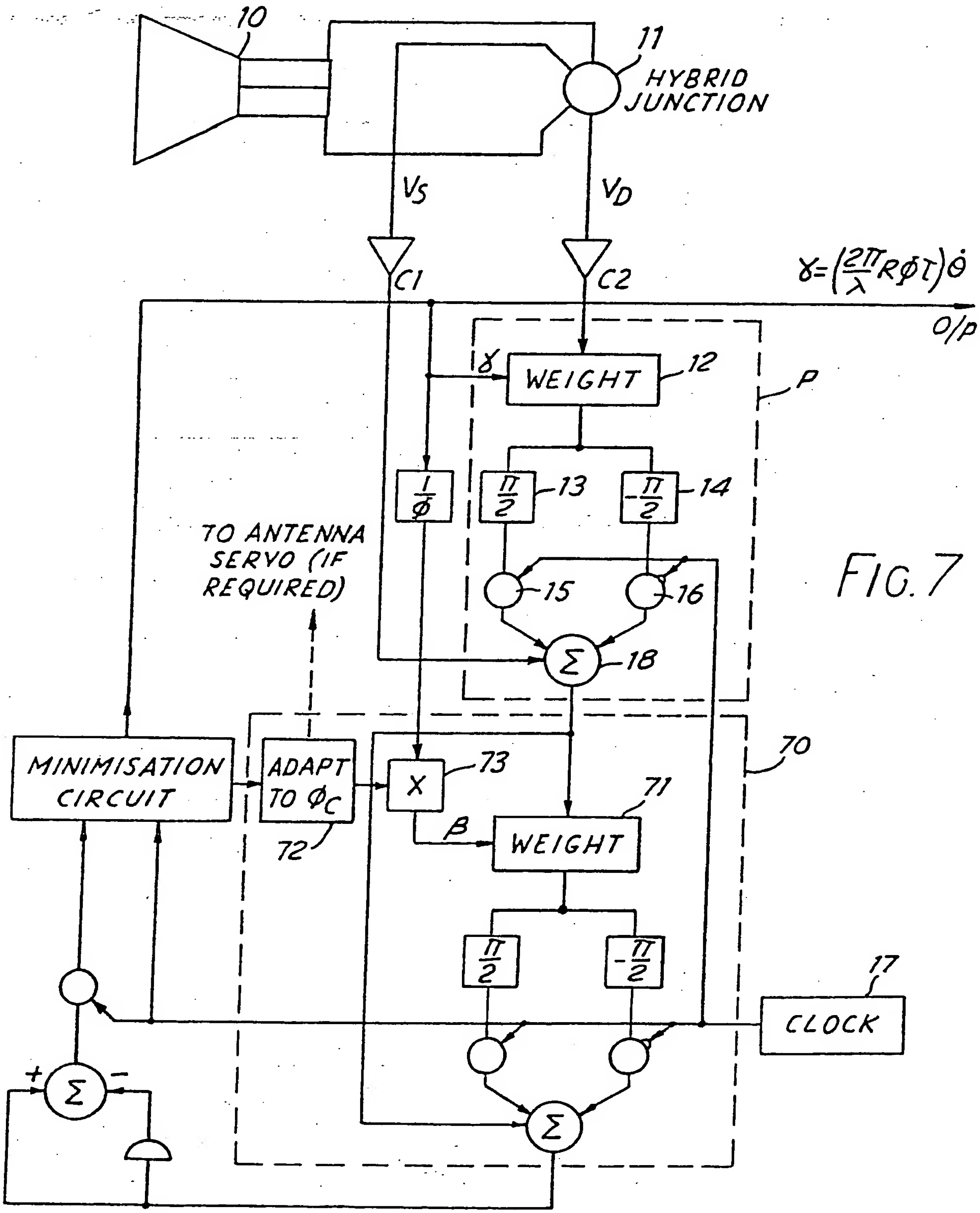

10
11
HYBRID JUNCTION
V_S
V_D
C1
C2
$\gamma = \left(\frac{2\pi}{\lambda} R \phi \tau\right)\dot{\theta}$
O/P
γ
WEIGHT
12
P
$\frac{1}{\phi}$
$\frac{\pi}{2}$
13
$-\frac{\pi}{2}$
14
TO ANTENNA SERVO (IF REQUIRED)
15
16
18
70
MINIMISATION CIRCUIT
ADAPT TO ϕ_C
72
X
73
71
β
WEIGHT
$\frac{\pi}{2}$
$-\frac{\pi}{2}$
17
CLOCK
+
−

FIG. 7

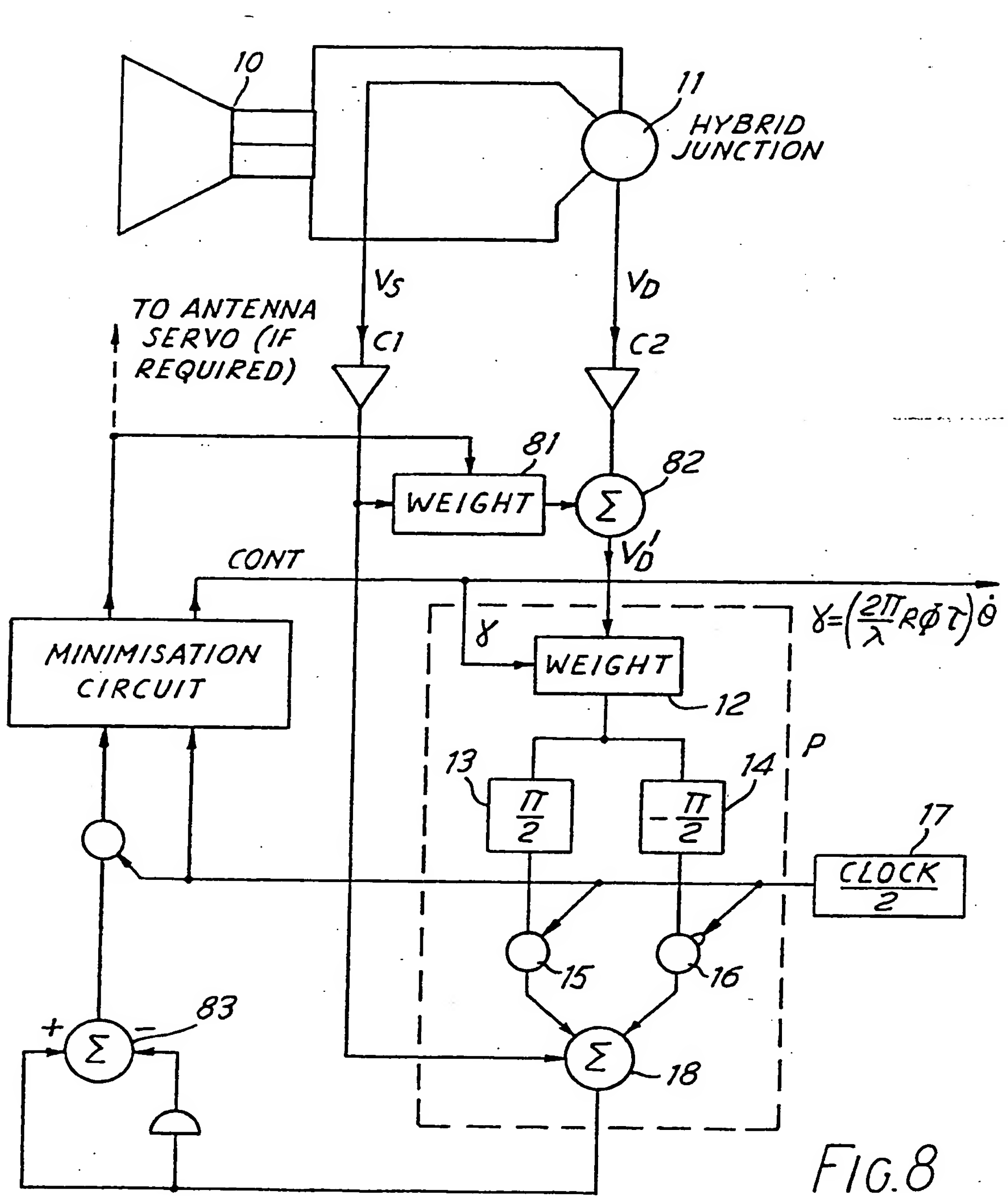

10
11
HYBRID JUNCTION
V_S
V_D
TO ANTENNA SERVO (IF REQUIRED)
C1
C2
81
82
WEIGHT
Σ
V_D'
CONT
$\gamma=\left(\frac{2\pi}{\lambda}R\bar{\phi}\tau\right)\dot{\theta}$
MINIMISATION CIRCUIT
γ
WEIGHT
12
P
13
14
$\frac{\pi}{2}$
$-\frac{\pi}{2}$
17
CLOCK 2
15
16
83
+
−
Σ
18

FIG.8

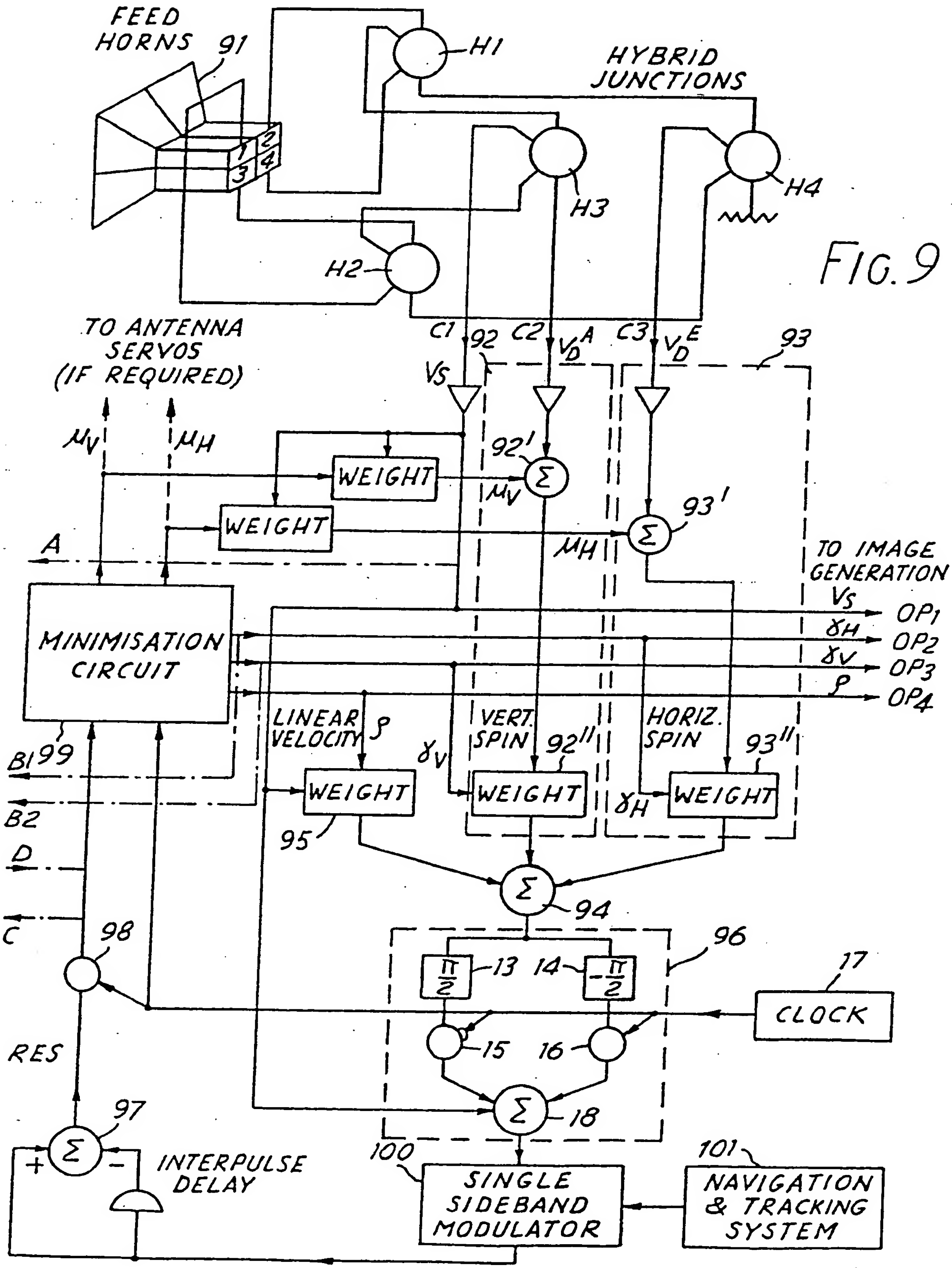

FEED HORNS
91
H1
HYBRID JUNCTIONS
H2
H3
H4
TO ANTENNA SERVOS (IF REQUIRED)
C1
C2
C3
92
93
Vs
V_D^A
V_D^E
μ_V
μ_H
WEIGHT
WEIGHT
92'
93'
A
TO IMAGE GENERATION
MINIMISATION CIRCUIT
Vs
γ_H
γ_V
ρ
OP1
OP2
OP3
OP4
LINEAR VELOCITY
VERT. SPIN
HORIZ. SPIN
92''
93''
99
B1
B2
WEIGHT
WEIGHT
WEIGHT
95
D
C
94
98
96
13
14
$\frac{\pi}{2}$
$-\frac{\pi}{2}$
17
CLOCK
15
16
RES
18
97
+
-
INTERPULSE DELAY
100
101
SINGLE SIDEBAND MODULATOR
NAVIGATION & TRACKING SYSTEM

FIG. 9

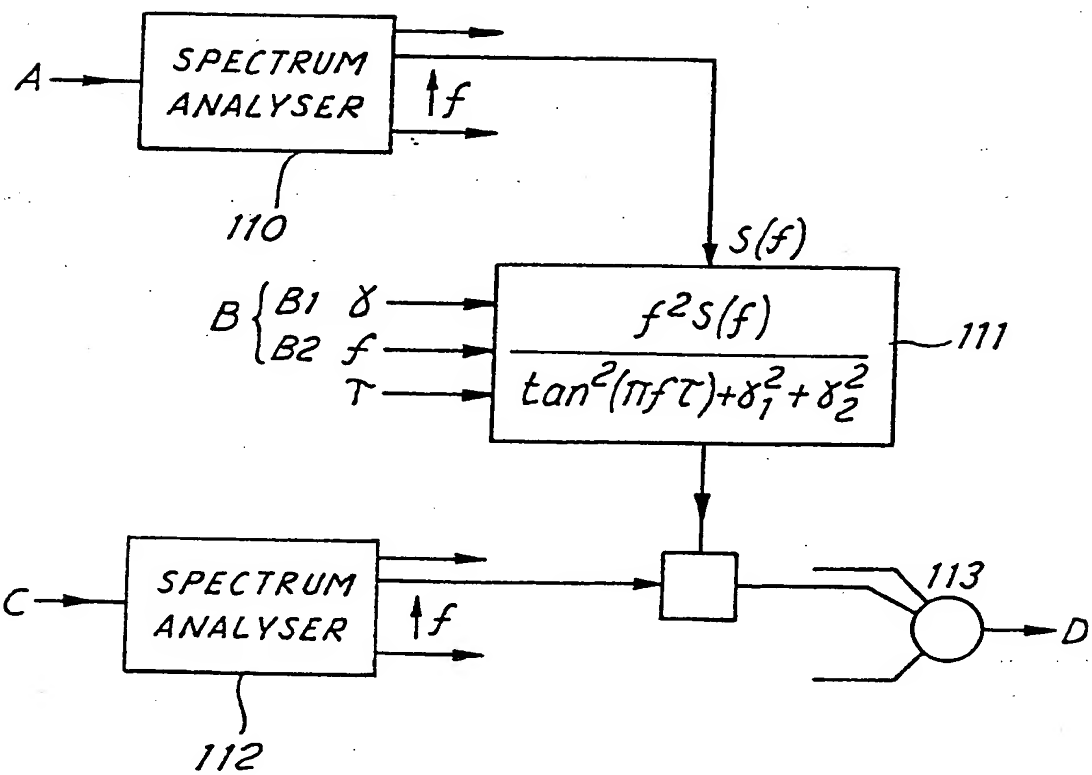

A
SPECTRUM ANALYSER
f
110
S(f)
B
B1 γ
B2 f
τ
$\frac{f^2 S(f)}{\tan^2(\pi f \tau)+\gamma_1^2+\gamma_2^2}$
111
C
SPECTRUM ANALYSER
f
112
113
D

FIG. 10

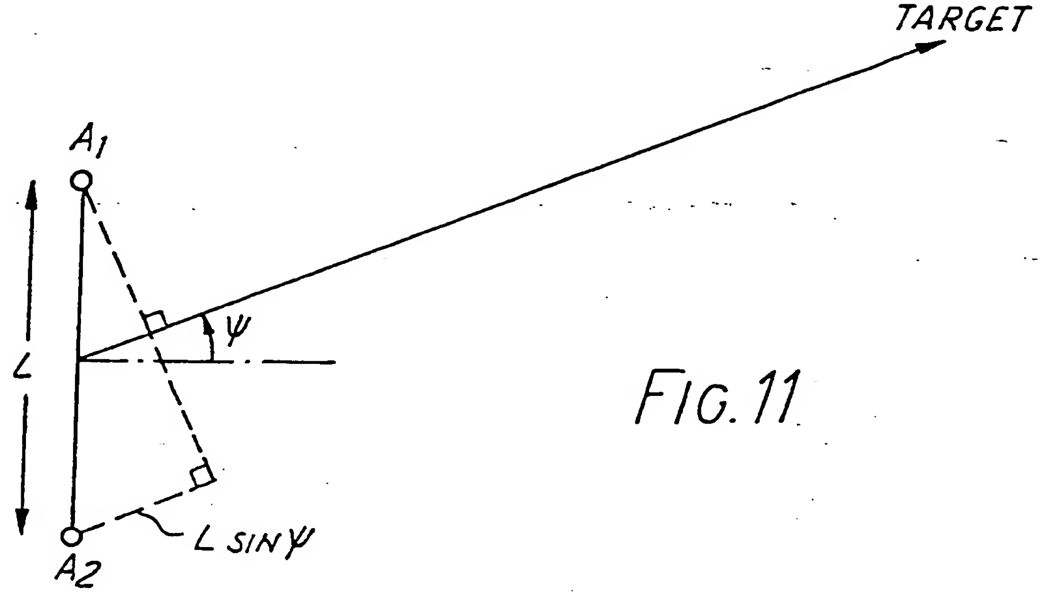

TARGET
A1
A2
L
ψ
L SIN ψ

FIG. 11

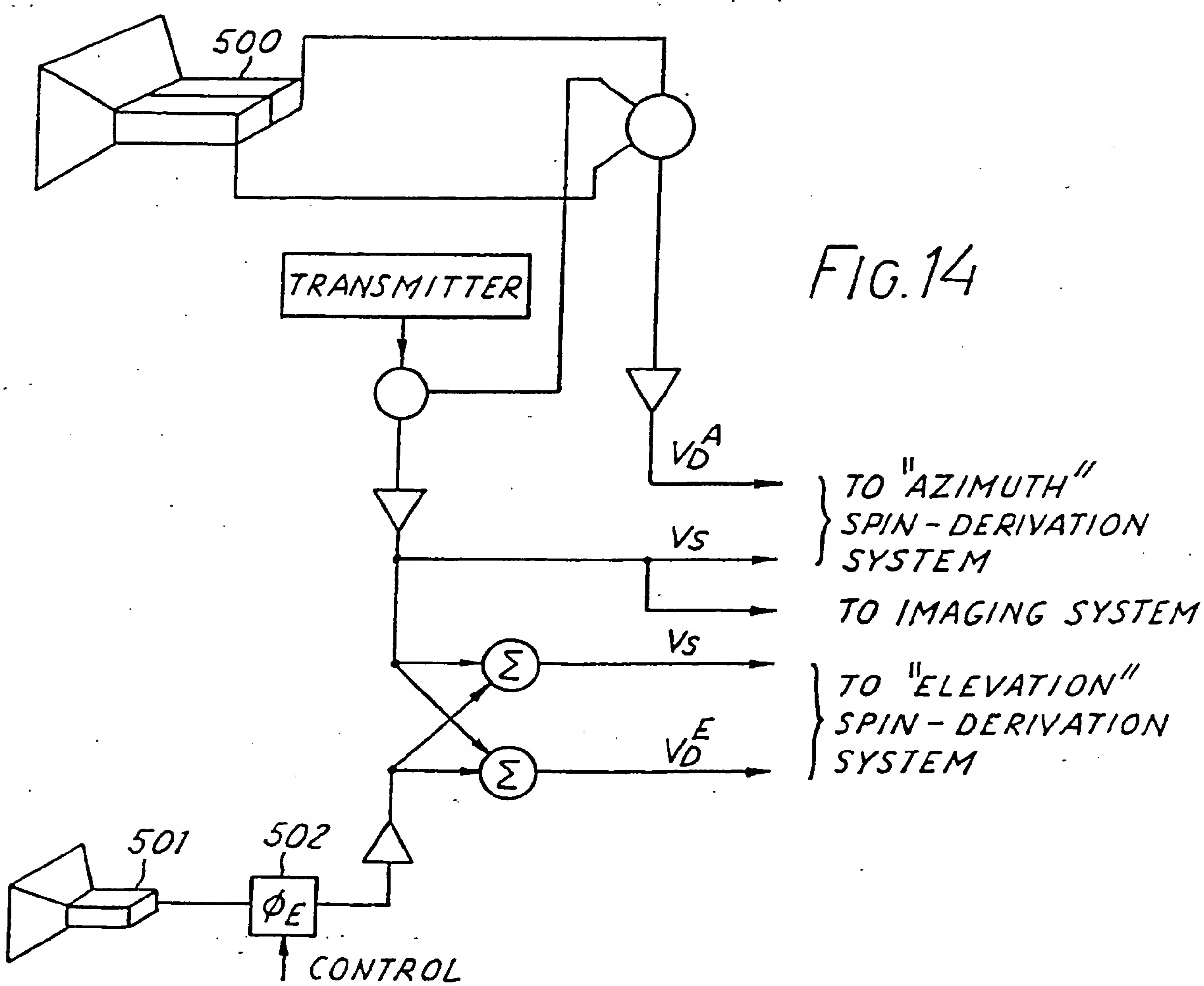
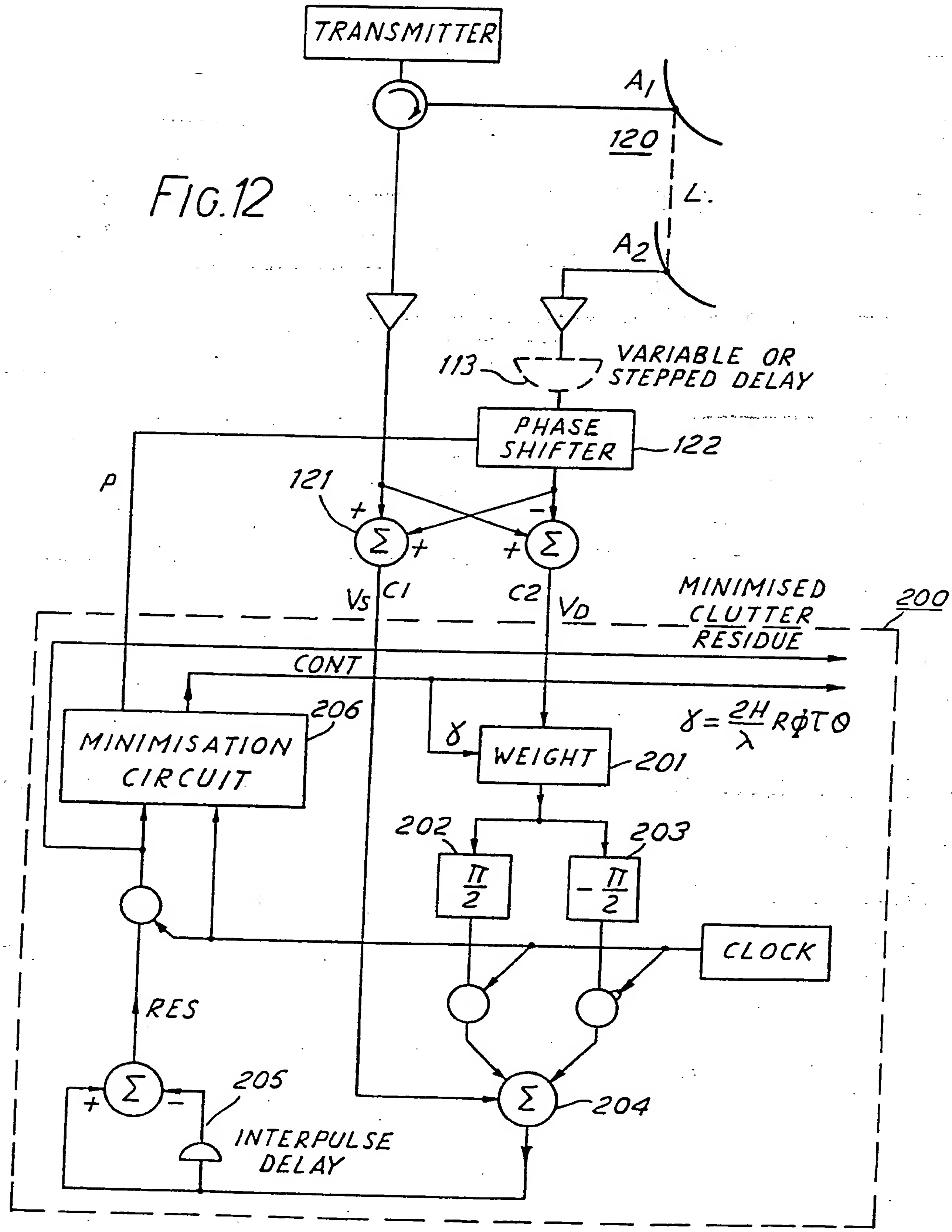
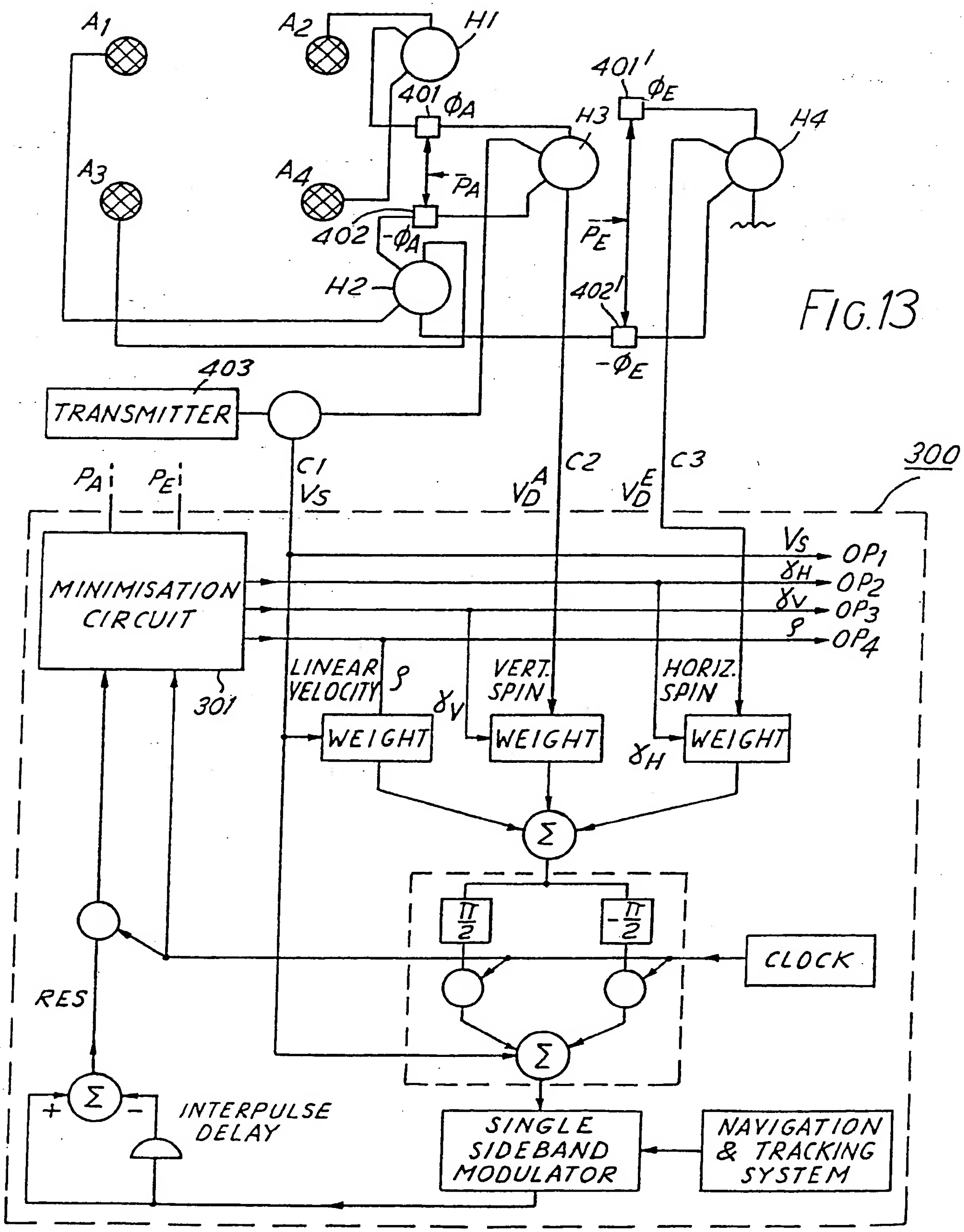

500
TRANSMITTER
VD A
TO "AZIMUTH" SPIN-DERIVATION SYSTEM
VS
TO IMAGING SYSTEM
VS
Σ
Σ
TO "ELEVATION" SPIN-DERIVATION SYSTEM
VD E
501
502
ΦE
CONTROL

FIG. 14

FIG.12


TRANSMITTER
A_1
120
L
A_2
VARIABLE OR STEPPED DELAY
113
PHASE SHIFTER
122
P
121
+
−
+
+
Vs
C1
C2
V_D
MINIMISED CLUTTER RESIDUE
200
CONT
206
MINIMISATION CIRCUIT
γ
WEIGHT
201
$\gamma = \frac{2H}{\lambda} R\phi T\theta$
202
203
$\frac{\pi}{2}$
$-\frac{\pi}{2}$
CLOCK
RES
205
INTERPULSE DELAY
204



A1
A2
A3
A4
H1
H2
H3
H4
401
401'
402
402'
ϕ_A
$-\phi_A$
ϕ_E
$-\phi_E$
P_A
P_E
403
TRANSMITTER
C1
V_S
C2
V_D^A
C3
V_D^E
300
MINIMISATION CIRCUIT
301
V_S OP1
γ_H OP2
γ_V OP3
ρ OP4
LINEAR VELOCITY
ρ
γ_V
VERT. SPIN
HORIZ. SPIN
WEIGHT
WEIGHT
γ_H
WEIGHT
Σ
$\frac{\pi}{2}$
$-\frac{\pi}{2}$
CLOCK
RES
Σ
+
−
INTERPULSE DELAY
Σ
SINGLE SIDEBAND MODULATOR
NAVIGATION & TRACKING SYSTEM

FIG.13

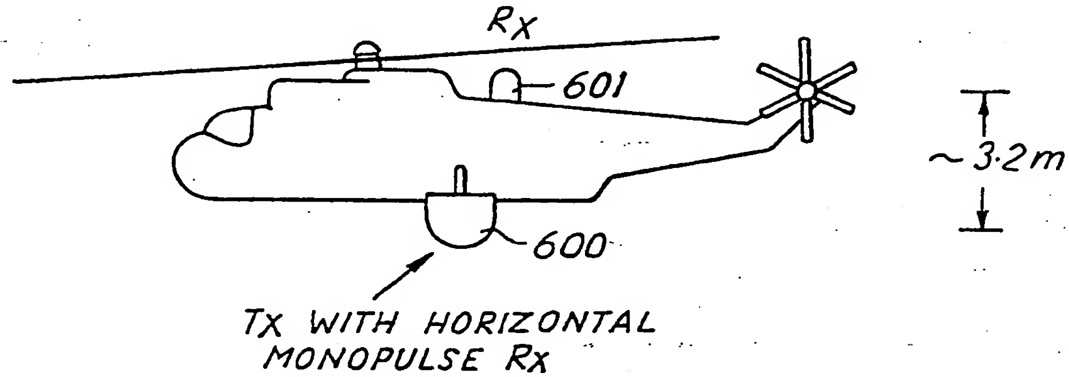

RX
601
~3·2m
600
TX WITH HORIZONTAL
MONOPULSE RX

FIG.15

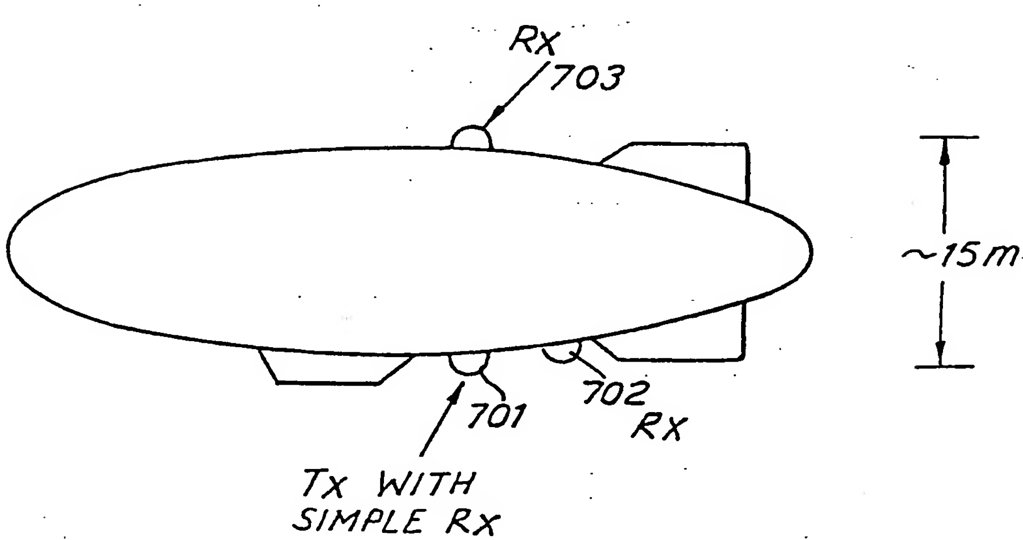

RX
703
~15m
701
702
RX
TX WITH
SIMPLE RX

FIG.16

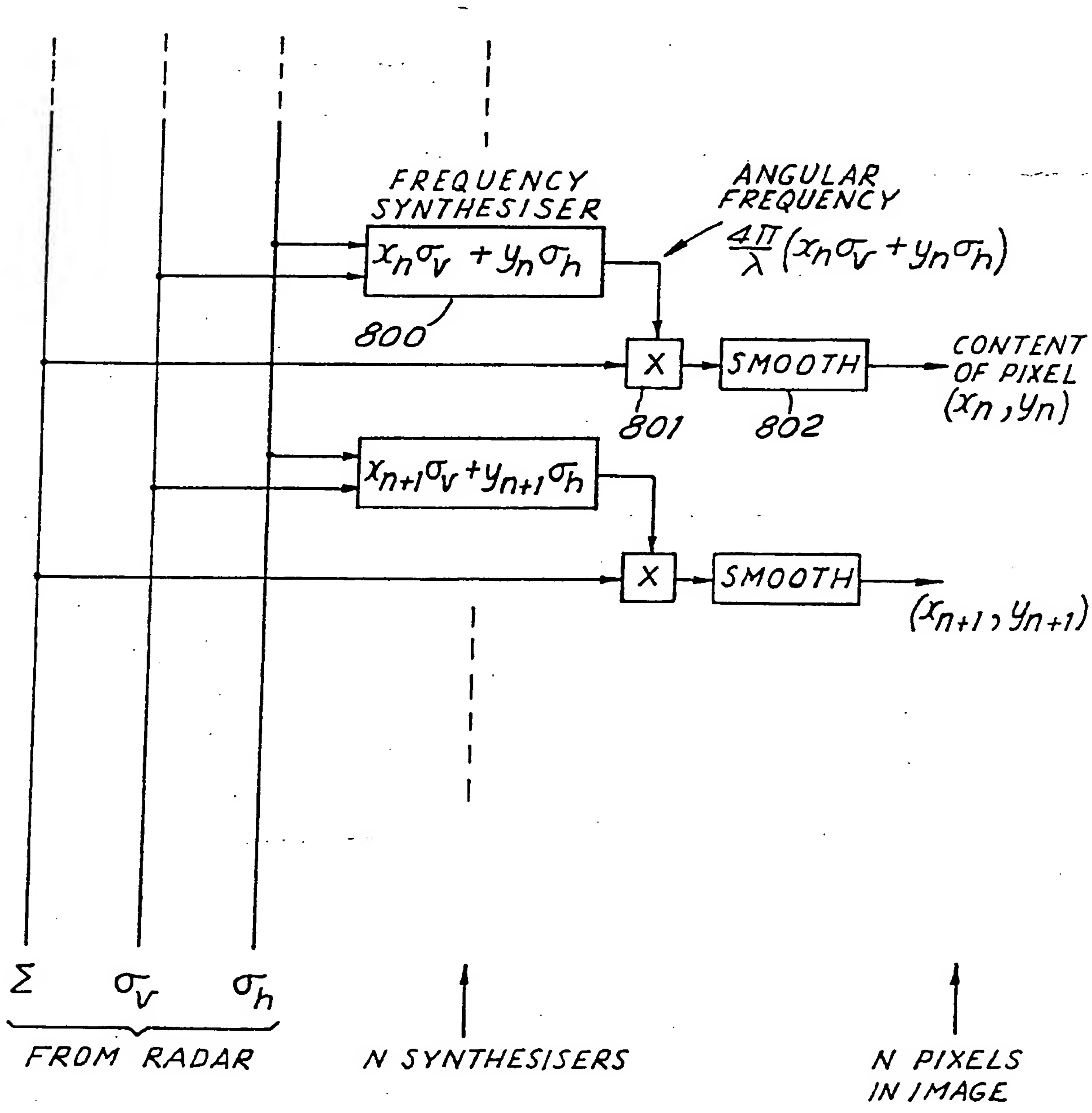

FREQUENCY SYNTHESISER
$x_n\sigma_v + y_n\sigma_h$
800
ANGULAR FREQUENCY
$\frac{4\pi}{\lambda}(x_n\sigma_v + y_n\sigma_h)$
X
801
SMOOTH
802
CONTENT OF PIXEL (x_n, y_n)
$x_{n+1}\sigma_v + y_{n+1}\sigma_h$
X
SMOOTH
(x_{n+1}, y_{n+1})
Σ
σ_v
σ_h
FROM RADAR
N SYNTHESISERS
N PIXELS IN IMAGE

FIG.17

A RADAR APPARATUS

This invention relates to a radar apparatus and it relates especially, although not exclusively, to a radar apparatus useful for determining one or more angular velocities of a target.

Doppler spectral broadening of returns from radar scatterers occurs as a result of the motion of the scatterers with respect to the radar. Such broadening may be due to a collective rotation of a group of radar scatterers about an axis. An example of Doppler spectral broadening arising in this manner occurs in returns from clutter (e.g. raindrops or chaff) which may exhibit a linear velocity gradient as a function of altitude due to the effect of wind shear. It would be desirable, generally, to reduce Doppler broadening produced in this way.

Similar Doppler broadening can also occur if the radar is mounted on a platform which moves relative to the target, as for example, in the case of a sideways looking airborne radar. The effect of linear platform motion normal to the line of sight can be eliminated by using a technique involving a displaced phase centre antenna. This technique is described in "Radar Handbook" ed M.I. Skolnik McGraw Hill 1970 p 18-7 et seq. The antenna is designed to produce sum and difference signals on receive, rather in the manner of a monopulse radar, the split plane of the antenna response beam being vertical. By

weighting successive pairs of difference signals in proportion to the resolved velocity of the aircraft and then combining these weighted signals in phase quadrature with the corresponding sum signals the resultant signals are made insensitive to Doppler broadening. This technique can be extended to eliminate the Doppler spread due to rotational motion of a target but this would require a knowledge of the relative motion of the target and radar and in general this information will ~~not-be-~~available.

Another example of Doppler broadening occurs in returns from a rotating target, such as a ship which may exhibit rotational motion due to pitch, roll or yaw movements. It has been shown in "Radar Target Imaging by Rotation About Two Axes" by R. Voles Proc IEE Oct. 1978 pp 919-921 that it is possible to construct an image of the target in two dimensions by rotating the target about two orthogonal axes in the cross-range plane of the radar and then analysing the spread of Doppler frequencies in returns. An image constructed in this way will generally have a better resolution than would be obtained without performing Doppler analysis. However, this technique can only be used if the angular velocities of the target about the two axes are known and, as before, this information will not in general be available.

It is an object of this invention to provide a radar which can be used to supress Doppler broadening due to the effect of wind shear on clutter or which alternatively can be used to

determine the angular velocity or velocities of a rotating target.

Accordingly there is provided a radar comprising an antenna arranged to produce a response beam having a sum pattern and a difference pattern and to generate, in response to a return, an electrical sum signal, corresponding to said sum pattern, and an electrical difference signal, corresponding to said difference pattern,

a processing-circuit to subject the difference signals, generated in response to a pair of consecutive returns, to respective changes of phase which are of equal magnitude and opposite sense and to change also the magnitudes of said difference signals by equal amounts,

means for combining vectorially each difference signal, subjected to said changes of phase and magnitude, with the corresponding sum signal thereby to generate a respective resultant signal,

and a control circuit for so varying the extent of said changes of magnitude as to cause a difference in the resultant signals, or signals related thereto, corresponding to a pair of consecutive returns, to approach a minimum value.

Doppler broadening due to the effect of vertical wind shear on clutter can be eliminated substantially by adjusting the extent of the magnitude change until the minimum value is attained. In the case of a radar used to monitor a target

undergoing rotational motion the extent of the magnitude change, necessary to attain a minimum, is related to the component of the angular velocity vector of the target along a respective axis.

In one embodiment the antenna may be capable of generating difference patterns lying in two, orthogonal planes. In these circumstances the antenna is arranged to produce a response beam having a first difference pattern in a first plane and a second difference pattern in a second plane, orthogonal to the first plane, and to generate, in response to a return, respective first and second electrical difference signals corresponding to said first and second difference patterns,

and first and second processing circuits are provided to operate respectively on said first and second difference signals, each said processing circuit being arranged to subject the corresponding difference signals, generated in response to a pair of consecutive returns, to respective changes of phase which are of equal magnitude and opposite sense and to change the magnitudes of said difference signals by equal amounts,

each said sum signal being combined vectorially with the corresponding difference signals, subjected to said changes of phase and magnitude, by said first and second processing circuits thereby to generate a resultant signal,

and said control circuit being arranged to so vary the extent of said changes of magnitude applied to said first and second difference signals as to cause a difference in

the resultant signals, corresponding to a pair of consecutive returns, to approach said minimum value. The angular velocity can be used to assist in production of a two dimensional image of the target.

Specific embodiments of the invention are now described by way of example only, by reference to the accompanying drawings of which,

Figure 1 shows one example of a single axis radar apparatus according to the invention,

Figure 2 represents schematically a rotating target (or clutter assembly) and is useful in understanding operation of the apparatus of Figure 1,

Figure 3 is a vector diagram useful in understanding operation of the apparatus of Figure 1,

Figure 4 shows another example of a single axis radar apparatus according to the invention,

Figure 5 is a vector diagram useful in understanding operation of the apparatus of Figure 4,

Figure 6 represents schematically a rotating target (or clutter assembly) having the rotational axis offset from the boresight of the radar,

Figure 7 shows a further example of a radar apparatus useful for compensating for an offset of the kind illustrated in Figure 6,

Figure 8 shows yet another example of a radar apparatus useful for compensating for an offset of the kind illustrated in

Figure 6,

Figure 9 shows a dual axis radar apparatus in accordance with the invention, and,

Figure 10 shows a circuit useful for causing an improvement in the effective signal-to-noise ratio of the receiver.

Figure 11 shows schematically two antennas arranged to operate as an interferometer,

Figure 12 shows an example of a single axis radar operating in accordance with this invention,

Figure 13 shows an example of a dual axis radar operating in accordance with this invention,

Figure 14 shows another example of a dual axis radar operating in accordance with this invention,

Figures 15 and 16 show two applications of dual axis radars, and

Figure 17 shows a circuit for forming a two dimensional image of a target using data generated by the apparatus of Figure 9.

The invention will be described initially by reference to Figure 1 which shows a radar having a monopulse antenna 10 for producing sum and difference patterns. As will become clear, hereinafter, if the antenna 10 is arranged to produce a difference pattern in a vertical plane (i.e. the split plane of the antenna lies in the horizontal plane) then the radar can be used to suppress Doppler broadening due to the effect of vertical wind shear on clutter such as raindrops or chaff. In

general, the difference pattern may be generated in the plane orthogonal to the rotational vector of a target and the radar can then be used to determine the angular velocity of the target about the respective axis.

As illustrated in Figure 2, both clutter subjected to wind shear and a rotating linear target can be perceived as an assembly of discrete scatterers, S(d) say, which lie on a straight line passing through the angular motion centre C and normal to the rotation vector. In this example, the boresight of the radar is also arranged to pass through the angular motion centre C. In these circumstances, the Doppler angular frequency $\omega(d)$ in returns from scatterer S(d) will be given by

$$\omega(d) = \frac{4\pi}{\lambda} v(d) \cos\alpha \simeq \frac{4\pi}{\lambda} v(d)$$

and as, $v(d) = d\,\dot{\theta}\cos\theta$

then $\omega(d) \simeq \frac{4\pi}{\lambda} d\,\dot{\theta}\cos\theta \simeq \frac{4\pi d\,\dot{\theta}}{\lambda} \longrightarrow$ Equation 1

where θ is the tilt of the line of scatterers (assumed small), α is the angle between the target normal at S(d) and the line of sight of S(d) from the radar (also assumed small) and d is the distance of S(d) from the axis of rotation.

Referring again to Figure 1, electrical signals representing returns received at the antenna 10 are applied to a processing circuit including a hybrid junction 11 which generates sum V_S and difference V_D signals in respective channels C1 and C2. The difference signals are weighted at 12 by an adjustable factor γ which is set adaptively in a manner described in detail hereinafter. Consecutively generated

difference signals are also subjected to phase shifts of equal magnitude but opposite sense; $+\pi/2$ and $-\pi/2$, in this example. Phase shifting circuits 13, 14 used for this purpose are connected in series with respective gating circuits 15, 16 which are held in the "open" condition alternately by pulses of opposite polarity generated by a clock 17 running at half the p.r.f. of the radar.

Each difference signal, adjusted in phase and amplitude in this way, is combined vectorially at 18 with the corresponding sum signal to generate a resultant signal R. Each resultant signal is then passed to a two pulse canceller comprising a delay 19, equal to the interpulse transmission interval τ of the radar and a subtractor 20 which subtracts the latest signal from the immediately preceding signal, delayed by τ. In this way the resultant signals corresponding to consecutive returns are compared by the canceller and any residual signal is generated at its output. A gate 21 ensures that residual signals derived only from successive pairs of consecutive returns are fed to a minimisation circuit, shown generally at 22. As will be described hereinafter this circuit operates in a servo loop and generates a variable control signal (CONT), of magnitude γ, which is fed to circuit 12 to drive the applied weighting in a sense appropriate to reduce the residual signal produced at the output of the two pulse canceller.

Operation of the above-described arrangement will be appreciated by reference to the vector diagram shown in Figure

3. The primed and unprimed vectors correspond respectively to returns from a single scatterer (S(d), in this case) corresponding to consecutive pulses and it will be seen that, as described hereinbefore, the difference signals $s(d)\Delta$, $s(d)'\Delta$, where Δ is the antenna voltage gain in the difference channel (a function of ϕ and hence d), and $s(d)\Delta$ is the voltage in the difference channel due to S(d), have been weighted by the factor γ and have been subjected also to respective phase shifts of $+\pi/2$ and $-\pi/2$. If it is assumed that the sum and difference channels of the receiver are substantially free from noise, the effect of Doppler broadening, whether due to wind shear or the relative rotational motion of a target and radar, will be eliminated by setting γ at an optimum value such that the resultant signals R, R' are coincident, and it can be seen from the geometry of the vector diagram that this condition prevails

when $\tan^{-1}\left(\frac{\gamma\, s(d)\Delta}{s(d)\Sigma}\right) = \frac{\omega(d)\tau}{2}$, where $\omega(d)$ is the Doppler angular frequency of the scatterer S(d), τ is the interpulse interval and $S(d)\Sigma$ is the voltage in the sum channel. The sum and difference patterns are designed so that

$$\frac{s(d)\Delta}{s(d)\Sigma} = \frac{d}{\Phi R}$$

where Φ is the antenna beam width and R is the range, so that when $\frac{\omega(d)\tau}{2}$ is small, as will generally be the case,

$$\gamma = \frac{2\pi}{\lambda} R \Phi \tau \dot{\theta} \longrightarrow \qquad \text{Equation 2}$$

Since γ is independent of the identity of the scatterer chosen this value must be the optimum for all scatterers in the assembly. Initially the value of γ selected may be such that the resultant signals R, R' are not coincident, and this is the situation illustrated in Figure 3. Circuit 22 is then used to drive the control signal (CONT), and so the value of γ, in a sense appropriate to reduce the residual signal at the output of the two pulse canceller. When a minimum is attained the resultants R, R' ~~will be~~ coincident.

This method can be used to supress Doppler broadening due to wind shear. When the optimum value of γ is achieved, the clutter residue at the canceller output will be minimised whilst returns from desired targets with steady Doppler components will pass through the canceller substantially unaffected. If, on the other hand, the radar is used to process returns from a rotating target then the optimum value of γ will, in noise free conditions, be directly proportional to the angular velocity of the target; in the case of an antenna difference pattern in the vertical plane, for example, this will be the angular velocity about the horizontal axis which, from Equation 2 is given by

$$\dot{\theta} = \frac{\lambda}{2\pi R \Phi \tau}\gamma$$

, R, Φ and τ being known, preset system parameters.

The optimum value of γ can be arrived at in a number of different ways. In one arrangement, for example, the control signal (CONT) may be perturbed so that γ is caused to oscillate between two similar values, the mean of which is driven until

the residual signal generated at the output of 20 shows no fluctuation at the frequency of oscillation. The optimum value of γ, commensurate with a minimum in the residual signal, will then have been found.

An alternative approach is illustrated in Figure 4. The resultant signal R corresponding to each return is formed, as before, in the main channel of the radar, shown generally at 40. In addition, however, a small fraction α of the difference channel signal is respectively added to (at 41) and subtracted from (at 42) the resultant signal, in phase quadrature with the sum channel component of the resultant signal, so as to form modified resultant signals R_+, R_-. Corresponding resultant signals, modified in this way and derived from consecutive returns, are then applied to respective two pulse cancellers 43, 44 the outputs of which are compared, after smoothing, in a further two pulse canceller 45.

In order to normalise the loop gain any difference between the outputs of cancellers 43, 44 is divided at 46 by their sum, as shown, and the normalised difference is then applied to an integrating circuit which generates the control signal CONT, of magnitude γ, applied to circuit 12. Corresponding modified resultant signals derived from consecutive radar returns are illustrated in the vector diagrams of Figures 5a and 5b. When γ has been set at the optimum value such that the unmodified resultant signals R, R' are coincident then the corresponding modified resultant signals, R+ R+' and R- R-',

shown in Figures 5a and 5b respectively, will generate respective residual signals RES+, RES- which are of equal magnitude but opposite direction. In this circumstance, the output of two pulse canceller 45 will be zero. The circuit is driven, therefore, until this zero condition is attained, and the output of the integrator 47 will then have a magnitude equal to the optimum value of γ.

The arrangements described thus far rely on the assumption that the boresight of the radar intersects with the axis of rotation of the linear array of scatterers. Particularly in the case of a target at long range this assumption is unlikely to be valid in all circumstances and when, as shown in Figure 6, the boresight is offset by an angle ϕ_c the direction of zero Doppler angular frequency will no longer coincide with the antenna boresight. In terms of a distance D from the intersection of the radar boresight with the array of scatterers the angular frequency in returns from scatterer S(d) can be expressed as

$$\omega(D) \simeq \frac{4\pi\dot{\theta}}{\lambda}(D - R\phi_c) = \frac{4\pi}{\lambda}\dot{\theta}\, d \longrightarrow \qquad \text{Equation 3}$$

where, as before, d is measured from the axis of rotation of the array.

We now find that

$$\frac{s(d)\Delta}{s(d)\Sigma} = \frac{D}{\Phi R}\left(= \frac{d + \phi_c R}{R\Phi}\right) \longrightarrow \qquad \text{Equation 4}$$

$$\text{Now, } \frac{\gamma s(d)\Delta}{s(d)\Sigma} = \tan\left(\frac{\omega(D)\tau}{2}\right)$$

$$\simeq \frac{\omega(D)\tau}{2} \longrightarrow \qquad \text{Equation 5}$$

And so, from equations 3, 4 and 5

$$\gamma = \frac{2\pi}{\lambda} R \bar{\Phi} \Gamma \dot{\theta} \frac{d}{D},$$

which is no longer independent of d. This problem can be remedied by shifting the Doppler frequency of all scatterers by an amount $\frac{4\pi}{\lambda}\dot{\theta}R\,\phi_c$. The required shift can be generated by including in the radar an additional servo loop shown generally at 70 in Figure 7 and which is used to follow the common offset frequency $\frac{4\pi}{\lambda} R\dot{\theta}\,\phi_c$.

As in the case of the arrangements already described, resultant signals R, R', corresponding to consecutive returns, are formed successively at the output of a primary circuit P by combining, vectorially respective sum signals V_S with the corresponding difference signals V_D modified, in amplitude, by the adjustable weighting factor γ, and in phase by $+\pi/2$ and $-\pi/2$ respectively. The reference numerals in circuit P correspond to those used in Figure 1. In addition, circuit 70 is arranged to weight, at 71, consecutive resultant signals R, R' by a further adjustable factor β , the weighted resultant signals being then added to, and subtracted from, the respective unweighted resultant signals in phase quadrature. The value of β is set adaptively also and will be approximately $\left(\frac{4\pi}{\lambda} R\,\phi_c\,\dot{\theta}\right)\gamma/2 = \frac{\gamma\,\phi_c}{4}$ when compensation for the offset frequency $\frac{4\pi}{\lambda} R\,\phi_c\dot{\theta}$ has been fully effected. In so far as γ, which is proportional to $\dot{\theta}$, will be varying much faster than ϕ_c the additional servo loop may be relatively quiescent by

arranging that ϕ_c be set independently at 72 and then multiplying the set value (at 73) by $\frac{\gamma}{\Phi}$. The value of ϕ_c may then be fed, if required, to the antenna pointing servo to drive the antenna into line with the axis of rotation of the target. As before the value of γ generated at the output O/P of the system can be used to derive the spin velocity of the target.

Figure 8 shows an alternative arrangement which can be used to compensate for the offset in antenna boresight direction. In this arrangement ~~an~~ adjustable component of each sum signal V_S is generated by a weighting circuit 81 and is added at 82 to the corresponding difference signal V_D to form a modified difference signal V_D' whose response pattern has a null in a direction dependent on the weight applied. The modified difference signal is then passed to a circuit P of the form described in relation to Figure 1. Again, the reference numerals in circuit P correspond to those of Figure 1. By adapting the additional loop to minimise any residual signal generated at the output of the two pulse canceller 83 the null in the response pattern of the modified difference signal V_D' will be caused to point in the direction intersecting the axis of rotation of the target. As before the weighting applied at 81 to each sum signal may be used to servo the antenna.

The systems described in relation to Figures 1, 4, 7 and 8 all involve use of an antenna difference pattern in one plane only and are capable of generating data relating to the angular velocity of a target about the corresponding rotation axis

normal to the plane of the difference pattern. It is possible to extend this principle to a dual axis system and a suitable arrangement is shown in Figure 9. The dual axis system, in the illustrated example, has an antenna 91 comprising four elements (1, 2, 3, 4) arranged in square formation so defining pairs of elements 1, 2; 3, 4 and 2, 4; 1, 3 in mutually orthogonal planes i.e. the horizontal and vertical planes. The elements forming the antenna are connected to an arrangement of hybrid junctions H1 - H4 which produce in respective channels C1, C2 and C3 a sum signal V_S representing the returns received at all the elements, an azimuthal difference signal (V_D^A) representing the difference of returns received at the pairs of elements 1, 3 and 2, 4 and an elevation difference signal (V_D^E) representing the difference of returns received at the pairs of elements 1, 2 and 3, 4.

The azimuthal and elevation difference signals are modified in respective circuits 92, 93, in the manner described hereinbefore in relation to Figure 8. Thus, circuits 92', 93' are used to add, adaptively respective components of the sum signal $\mu_V V_S$, $\mu_H V_S$ to the difference signals (V_D^A, V_D^E) thereby to compensate for the effect of a radar boresight offset from the direction of the centre of motion. Circuits 92", 93", on the other hand, are used, as before, to apply adaptively appropriate weighting factors γ_V, γ_H, related to respective horizontal and vertical angular velocities σ_V, σ_H of the

target. The weighted difference signals are combined in circuit 94 with the sum signal V_S, itself weighted in circuit 95 by a factor ρ related to the linear velocity of the target. Signals generated at the output of circuit 94 are passed to a circuit 96, of the kind described already in relation to Figure 1, where they are combined vectorially with corresponding sum signals to form respective resultant signals.

The resultant signals corresponding to consecutive returns are then compared in a two pulse canceller 97 and any difference is represented as a residual signal RES formed at its output. Gate 98 ensures that residual signals corresponding to successive pairs of consecutive returns are passed to a minimisation circuit 99 where the values of γ_H, γ_V, μ_H, μ_V and ρ are adjusted adaptively until a minimum in the residual signal is attained, γ_H and γ_V being then proportional to the respective horizontal and vertical angular velocities σ_H, σ_V of the target. The values of V_S, γ_H, γ_V, and ρ are formed at respective output locations OP1 - OP4, and as before μ_H and μ_V may be used to servo the antenna. The target and radar will have a known closing velocity measured typically by means of a central navigation system and radar tracking system 101. A single side band modulator 100 is provided in the arrangement of Figure 9, prior to the two pulse canceller 97, to compensate for this velocity and the weighting factor ρ is applied to compensate for any error in the servo loop caused by modulation.

It will be appreciated that the arrangement described in relation to Figure 9 may be adapted to function alternatively in the manner described by reference to Figures 4 or 7.

It has been assumed in the embodiments described thus far that the sum and difference channels of the receiver are substantially free from noise. In some operational conditions, however, the signal-to-noise ratio may be relatively poor and it may not be possible to achieve exact cancellation of the resultant signals R, R' corresponding to pairs of consecutively transmitted pulses. In these circumstances the value of the weighting factor γ_{min}, corresponding to a minimum in the residual signal produced at the output of the two pulse canceller may not be related to the angular velocity $\dot{\theta}$ of a rotating target by the expression defined herein - Equation 2. If it is assumed that the probability density function of noise in the two channels varies with amplitude in accordance with a Gaussian distribution then the effect of noise is to modulate the r.f. carrier signal with an envelope function whose amplitude conforms to a Rayleigh distribution.

To reduce the effect of noise an average residue R_{AV} can be derived from a large number (100, say) of resultants R, R' corresponding to consecutive pulse pairs. The value of γ which minimises R_{AV}, $\gamma^{*}min$ can be shown to be related to γ, defined in Equation 2, by the approximate expression

$$\gamma^{*}_{min} \doteq \frac{\gamma}{\left[1 + \dfrac{\langle \nu^2 \rangle}{1 + 4\,\overline{\nu^2}\;\overline{\cos^2(\phi PA)}}\right]} \rightarrow \text{Equation 6}$$

where $\langle \nu^2 \rangle$ is the mean square value of the Gaussian noise components, ν is the ratio of the components of the difference channel and sum channel returns from a given scatterer and $\overline{\nu^2}$ is the averaged value of the square of this quantity over all scatterers, and ϕ_{PA} is half the phase angle between successive returns of the components of the sum channel from a given scatterer and $\overline{\cos^2(\phi_{PA})}$ is the averaged value of the square of the cosign of this quantity over all scatterers.

To alleviate the effect of noise the effective signal-to-noise ratio in the receiver may be improved by suitably weighting different frequency components in the power density spectrum produced at the output of the two pulse canceller. In this way the denominator in Equation 6 can be made to approach unity so that γ^*_{min} approaches γ. It will be assumed, for convenience, that the power density spectrum of noise due to the sum channel, observed at the output of the canceller, is proportional to $\sin^2(\pi f \tau)$, where f is the frequency component considered and that the power density spectrum of noise, due to the difference channel, is proportional to $\cos^2(\pi f \tau)$. It can be shown that a significant improvement in the signal-to-noise ratio is achieved by weighting respective frequency components of the power density spectrum produced at the output of the canceller by a

function $W(f)$ of the form

$$W(f) = \frac{f^2 \; S(f)}{\tan^2(\pi f \tau) + \gamma^2} \longrightarrow \qquad \text{Equation 7}$$

where $S(f)$ is the f^{th} frequency component of the power density spectrum in the sum channel prior to the canceller.

A circuit suitable for implementing this technique is shown in Figure 10, input and output locations (A, B, C and D) of the circuit being shown both in Figures 1 and 9.

The signal in the sum channel is subjected in a first spectrum analyser 110 to frequency analysis and respective frequency components $S(f)$ are passed to a processor 111 arranged to evaluate weighting factors of the form defined in Equation 7. To this end the current value of γ is fed to the processor via input location B. Signals indicative of the pulse repetition period τ and frequency f are also passed to the processor. Signals produced at the output of the two pulse canceller are passed, via input location C, to a second spectrum analyser 112 and the frequency components, so produced are weighted by respective amounts evaluated in processor 111. The weighted frequency components are then summed at 113 and applied to the minimisation circuit (32 in Figure 1) via an output location D. In the case of a dual axis system, of the kind shown in Figure 9, the term γ^2 in Equation 7 will be replaced by the term $\gamma_V{}^2 + \gamma_H{}^2$. It will be appreciated that alternative forms of weighting function $W(f)$ may be used.

It will be appreciated that by scaling the Doppler

frequencies of returns from a target in proportion to the angular velocity of the target, determined in accordance with the present invention, it is possible to construct a projection of the target onto the direction normal to the angular velocity vector in the cross-range plane.

It can be shown that a radar apparatus of the kind described hereinbefore in accordance with the invention has a linear resolution r in the crossplane at the target (i.e. the plane at the target normal to boresight) and to a first approximation

$$r \propto \frac{R\,\overline{\Phi}}{\sqrt{\rho_o M}} \longrightarrow \qquad \text{Equation 8}$$

where R is target range,

$2\,\overline{\Phi}$ is the antenna beam width of the sum pattern, ρ_o is the single pulse S/N ratio in the sum pattern (i.e. the ratio of the total radar cross-section to thermal noise) and M is the ratio of the PRF of the radar to the bandwidth of observed target angular frequencies.

In another embodiment the inventor has appreciated that the resolution r can be improved if the slope ($1/\overline{\Phi}$) at the origin of the difference pattern is increased provided there is no significant reduction in antenna aperture.

The inventor has found that, in the case of a single axis radar, improved resolution can be achieved if the antenna comprises two discrete parts which are spaced apart so as to form, in effect, an interferometer.

This is demonstrated schematically in Figure 11 which shows

two antennas A_1 and A_2 spaced apart by a distance L. If the normal to the line connecting the antennas points at an angle ψ to the target direction, as shown, the angular period $\delta\psi$ between successive nulls in the sum and difference patterns will be given by

$$\delta\psi = \frac{\lambda}{L\cos\psi}$$

and the normalised slope at the origin of a null in the difference pattern, at angle ψ, is given by

$$\frac{1}{\Phi} = \frac{2\pi}{\delta\psi} = \frac{2\pi L\cos\psi}{\lambda} \longrightarrow \qquad \text{Equation 9}$$

Equation 9 suggests that the greater the value of L the greater will be the improvement in resolution; however the inventor has found that, in practice, there will be little significant improvement in resolution unless,

$$L\cos\psi < \breve{\dot{\Theta}}\tau R \longrightarrow \qquad \text{Equation 10}$$

where τ is the interpulse period and $\breve{\dot{\Theta}}$ is the smallest angular velocity to be determined.

Figure 12 shows one embodiment of a single axis radar arranged to operate in accordance with this principle. The antenna array shown at 120 comprises two antennas A_1 and A_2 which are spaced apart by a distance L and connected to a hybrid junction, shown generally at 121, which generates sum and difference signals V_S, V_D in respective channels C1 and C2. The hybrid junction is connected to a processing circuit 200 which operates in identical manner to that described hereinbefore in relation Figure 1. In brief the weighting factor γ is applied to the difference signal V_D at 201 and the respective phase shifts

$\pm \pi/2$ are applied at 202, 203. The difference signals, modified in phase and amplitude in this way, are combined vectorially at 204 with the respective sum signals to form resultant signals and consecutive resultant signals are compared in a two pulse canceller 205. Any residual signal RES is then applied to a minimisation circuit 206 which drives the weighting factor γ until the magnitude of the residual signal attains a minimum value. The weighting factor γ is then directly proportional to the angular velocity of a target rotating about a respective axis provided the null of the difference pattern is pointing at the motion centre of the target. In this example, the minimisation circuit 206 also generates a further control signal P which drives a phase shifter 122, connected in series with antenna A_2, to steer the nearest null in the difference pattern into alignment with the motion centre of the target. In addition, in the case of a radar having high range resolution a variable or stepped delay 113 may be introduced to compensate for the delay corresponding to the distance L sin ψ in Figure 11.

One or other of the antennas A_1 and A_2 may be used as a transmitter, or alternatively a separate transmit antenna could be provided. Moreover, the antennas A_1 and A_2 need not have identical gains provided the signal produced by the antenna having the greater sensitivity is suitable attenuated prior to formation of the sum and difference signals so that the effective sensitivities of the two antennas are equal. If this is the case, one of the antennas in a pair could be relatively

small and could, for example, be an unsteered omnidirectional antenna. The preferred condition expressed in Equation 10, can be satisfied either by adjusting the separation L of the antennas or, more conveniently, by varying ψ by rotating a platform on which the antennas are mounted.

The operating principle of the single axis radar can be extended to a dual axis radar used to generate sum and difference patterns in two mutually orthogonal planes, typically in azimuth and elevation. A suitable arrangement of antennas is shown in Figure 13. It comprises four spaced apart antennas A_1, A_2, A_3 and A_4 located at the corners of a square and connected to an arrangement of hybrid junctions H1-H4 which generate in respective channels C1, C2 and C3 a sum signal V_S representing returns received at all the elements, an azimuthal difference signal (V_D^A) representing the difference of returns received at the antenna pairs 1,3; 2,4 and an elevation difference signal (V_D^E) representing the difference of returns received at the antenna pairs 1,2; 3,4. The signals in the three channels are fed to a processing circuit shown generally at 300 of the kind described hereinbefore in relation to Figure 9. As in the case of a single axis radar, described in relation to Figure 12 of this application, the minimisation circuit 301 generates respective control signals P_A, P_E which are used to drive pairs of phase shifters 401, 402; 401', 402' to steer the nearest nulls in the azimuth and elevation difference patterns into alignment with the motion centre of the

target. A transmitter 403 is shown feeding all the antennas, in this example, although energy could alternatively be fed to a single antenna only or to a fifth antenna used solely as a transmitter. Although a dual axis radar having four antennas has been described an alternative construction could include three antennas arranged in respective pairs aligned in two orthogonal planes.

In some circumstances it may not be convenient to provide more than two antennas. However, as shown in Figure 14, a dual axis radar may still be constructed if a first antenna 500 operates as a monopulse antenna so as to generate sum in difference in the azimuthal plane, say, and a second antenna 501 is used in conjuction with the first to form therewith an interferometer generating sum and difference patterns in the elevation plane and operating in the manner described hereinbefore. Respective sum and difference signals are fed to separate processing circuits (not shown) of the kind already described. As before, a minimisation circuit in the processing circuit associated with the interferometer generates a control signal to drive a phase shifter 502 so as to steer the nearest null in the difference pattern generated by the antenna pair 500, 501 into alignment with the centre of motion of the target.

A particular application of this arrangement is on an aircraft such as a helicopter, as shown in Figure 15. In this case a single-axis monopulse antenna 600 is mounted below the helicopter so as to be capable of generating sum and difference

patterns in the horizontal plane whereas a steered receiving antenna 601 is mounted in a radome on top of the aircraft directly above antenna 600 to form therewith an interferometer capable of generating sum and difference patterns in the vertical plane.

In an alternative arrangement shown in Figure 16 three antennas could be mounted on an airship. As illustrated, two of the antennas 701, 702 are mounted below the ship to form an interferometer capable of generating sum and difference patterns in the horizontal plane and the third antenna 703 being used in conjunction with one of the others to form an interferometer capable of generating sum and difference patterns in the vertical plane.

It will be appreciated that in all the embodiments described hereinbefore processing may be either at RF or IF or can be effected at base band using phase and quadrature (i.e. I and Q) channels. Moreover processing may be effected either digitally or in analogue or in hybrid fashion.

Although a preamplifier is shown in each receive channel in the illustrated examples weighting, phase shifting etc. could be effected alternatively at RF prior to use of a single preamplifier stage. Also, although the gating arrangements used in the above-described examples are organised to produce one residual signal for each successive pair of returns it is possible alternatively to generate a residual signal at each return; in this latter case each difference signal will be

subjected to both positive and negative phase shifts and a positive phase shift will be delayed by an inter-pulse period and compared with a subsequent resultant signal derived from the corresponding sum and difference signals with negative phase shift.

The values of σ_V, σ_H and V_S formed in a dual axis arrangement of the kind described by reference to Figure 9 may be used to assist in production of a two dimensional image of the target in the plane containing both axes and, in particular, may be used to image a ship undergoing both yaw and roll motions when viewed from broadside. An arrangement for carrying out such imaging is now described by reference to Figure 17.

It is assumed that each pixel in the image plane has vertical and horizontal co-ordinates x, y respectively. A frequency synthesiser 800 is provided for each pixel and generates a synthesised signal having a constant amplitude and an angular frequency given by

$$\omega_s = \frac{4\pi}{\lambda}(x\sigma_V + y\sigma_H)$$

This signal is correlated in a mixer 801 with the common sum signal V_S and the output is smoothed at 802. The synthesised signal generated in respect of each pixel will extract from the sum signal a component proportional to the scattering strength of the target at the respective pixel. Processing of this kind can be effected in a number of alternative ways including analogue or digital computing and real time or off line processing etc.

Insofar as the spatial resolution of the target will collapse to zero when the total rotation vector has collapsed to zero, it will be advantageous to arrange for the resultant of σ_V and σ_H to be continuously computed and for the outputs of the mixers to be inhibited whenever the resultant falls below a preset level. Likewise, if different linear resolutions are acceptable along the two imaging axes, the inhibition can be arranged to operate whenever either rotational motion falls below the corresponding one of two preset thresholds.

An alternative approach results from considering the Doppler spectrum in the sum signal to be a "projection" of the target image onto a line in the cross-range plane which is orthogonal to the instantaneous total rotation vector of the target formed by combining the components σ_V, σ_H; and the "scale" of the projection (i.e., the factor relating frequency to linear distance in the image plane) in these circumstances is proportional to the magnitude of the total rotation vector. As the rotation angle and magnitude are measured by the radar they can be used to construct an image using known techniques similar to those that have been evolved for computer-aided tomography. When the rotation magnitude is low the "scale" will also be low and so the resolution will be poor; so criteria can be established so that such projections are not used in the construction. Another "editing" possibility is that when the adventitious motion of the ship has led to "oversampling" in some projective regions, the corresponding data can be

deweighted accordingly. If the construction were effected off-line so that the whole record is available prior to construction, then the trajectories of the rotation magnitude and angle would be analysed in the first instance to establish the optimum weight to give to each Doppler spectrum (i.e., each short section of the signal) when it is used in the construction.

It has been assumed hereinbefore that the target is entirely contained within a single range cell. In practice, of course, with a radar having a high pulse bandwidth, the target will be quite well resolved in range; in the case of a ship, for example, viewed at 45° from end-on its length, typically 120m, will be resolved into 21 pixels in range by a radar having a resolution of 4m.

Irrespective of the range resolution of the radar, the derivation of the target rotation must be made by using returns from over the whole of the target. That this is so is apparent from the fact that when the target ship is viewed broadside-on (for instance) the yaw rotation is determined principally by scatterers at the extremeties of the superstructure while roll rotation is derived from returns near the centre.

It is possible therefore to use the high range resolution of a radar to track the target and then to gate through to the rotation-derivation circuits, described hereinbefore, all the returns from the ship - but, in so doing, to exclude clutter returns from up-and down-range of the ship.

A more elaborate scheme would be one in which a preliminary examination is made to ascertain the aspect of the target ship so that, thereafter, only the returns from the most relevant scatterers are gated-through to separate rotation-derivation circuits. In this case, therefore, the sets of radar data being used by the two rotation derivation circuits would generally be different.

Having derived the rotation velocity of the target ship, the reconstruction of the image in the cross-plane could be achieved by simultaneously using returns from the whole ship. Preferably, however, a cross-plane image would be constructed from the returns in each resolvable range cell so that the location of each scatterer would then be known explicitly relative to three orthogonal axes.

It is possible, therefore, to derive the three-dimensional range of the target together with its true scale and orientation.

There are clearly many ways in which this data could be presented to the operator or to an automatic classification system. So far as an operator display is concerned, a convenient arrangement is one in which the beam, bow and plan projections are displayed simultaneously, all at a standard scaling and with the plan projection oriented to the aspect angle of the ship during the observation period. Clearly, other arrangements are possible.

CLAIMS

1. A radar comprising an antenna arranged to produce a response beam having a sum pattern and a difference pattern and to generate, in response to a return, an electrical sum signal, corresponding to said sum pattern, and an electrical difference signal, corresponding to said difference pattern,

a processing circuit to subject the difference signals, generated in response to a pair of consecutive returns, to respective changes of phase which are of equal magnitude and opposite sense and to change also the magnitudes of said difference signals by equal amounts,

means for combining vectorially each difference signal, subjected to said changes of phase and magnitude, with the corresponding sum signal thereby to generate a respective resultant signal,

and a control circuit for so varying the extent of said changes of magnitude as to cause a difference in the resultant signals, or signals related thereto, corresponding to a pair of consecutive returns, to approach a minimum value.

2. A radar according to Claim 1 wherein said control circuit includes means for increasing, by equal amounts, the magnitudes of the difference components of the resultant signals, corresponding to a pair of consecutive returns, and for reducing said magnitudes by the same amounts, thereby to

generate respective pairs of modified resultant signals,

respective means for comparing the magnitudes of each said pair of modified resultant signals to generate respective comparison signals, and means for so varying the extent of said changes of magnitude, applied to respective difference signals to cause a difference in the magnitudes of said comparison signals to approach said minimum value.

3. A radar according to Claim 1 wherein said control circuit includes means for subjecting the resultant signals, generated in response to a pair of consecutive returns, to respective changes of phase which are of equal magnitude and opposite sense and to change also the magnitudes of said resultant signals by equal amounts, thereby to generate further resultant signals, and means for so varying the extent of the changes of magnitude applied both to said difference signals and to said resultant signals to cause a difference in the magnitude of said further resultant signals to approach said minimum value.

4. A radar according to Claim 1 including means to weight each said difference signal by a respective amount, related to the corresponding sum signal, and wherein said control circuit is arranged also to vary said respective amount.

5. A radar according to any one of Claims 1 to 4 wherein said antenna comprises first and second discrete parts which are spaced apart relative to one another.

6. A radar according to Claim 1 wherein said antenna is arranged to produce a response beam having a first difference

pattern in a first plane and a second difference pattern in a second plane, orthogonal to the first plane, and to generate, in response to a return, respective first and second electrical difference signals corresponding to said first and second difference patterns,

and first and second processing circuits are provided to operate respectively on said first and second difference signals, each said processing circuit being arranged to subject corresponding difference signals, generated in response to a pair of consecutive returns, to respective changes of phase which are of equal magnitude and opposite sense and to change the magnitudes of said difference signals by equal amounts,

each said sum signal being combined vectorially with the corresponding difference signals, subjected to said changes of phase and magnitude, by said first and second processing circuits thereby to generate a resultant signal,

and said control circuit being arranged to so vary the extent of said changes of magnitude applied to said first and second difference signals as to cause a difference in the resultant signals, corresponding to a pair of consecutive returns, to approach said minimum value.

7. A radar according to Claim 6 wherein said antenna comprises at least three antenna elements which are spaced apart relative to one another.

8. A radar according to Claim 6 wherein said antenna comprises first and second discrete parts which are spaced apart

relatively to one another so as to be capable of producing said first difference pattern, and one of said discrete parts being further capable of producing said second difference pattern.

9. A radar according to Claim 1 or Claim 6 including means for weighting, by respective amounts, different frequency components of a said difference in the magnitudes of the resultant signals corresponding to a pair of consecutive returns.

10. A radar according to any one of the preceding Claims wherein said respective changes of phase to which said difference signals, generated in response to a pair of consecutive returns, are subjected, are $\pi/2$ in magnitude.

11. A radar substantially as hereinbefore described by reference to and as illustrated in the accompanying drawings.

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Patents Act 1977
Examiner's report to the Comptroller under Section 17 (The Search Report)

Application number 8330943.5

Relevant Technical fields

(i) UK Cl (Edition F) H4D

(ii) Int Cl (Edition -)

Databases (see over)

(i) UK Patent Office

(ii) -

Search Examiner
H E GRIFFITHS

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Documents considered relevant following a search in respect of claims 1

Category (see over)	Identity of document and relevant passages	Relevant to claim(s)
	NONE	

SF2(p)

Category	Identity of document and relevant passages	Relevant to claim(s,

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